Topographic controls on shallow groundwater levels in a steep, prealpine catchment: When are the TWI assumptions valid?

Rinderer, Michael ; van Meerveld, H J ; Seibert, Jan

Abstract: Topographic indices like the Topographic Wetness Index (TWI) have been used to predict spatial patterns of average groundwater levels and to model the dynamics of the saturated zone during events (e.g., TOPMODEL). However, the assumptions underlying the use of the TWI in hydrological models, of which the most important is that groundwater level variation can be approximated by a series of steady state situations, are rarely tested. It is also not clear how well findings from existing hillslope studies on sites with transmissive soil can be transferred to entire catchments with less permeable soils. This study, therefore, evaluated the suitability of selected topographic indices to describe spatial groundwater level variations based on time series from 51 groundwater wells in a 20 ha catchment with low-permeability soils in Switzerland. Results showed that median groundwater levels were correlated to slope, curvature, and TWI, but the strength of correlation depended on whether the indices characterized the local topography or the topography of the upslope contributing area. The correlation between TWI and groundwater levels was not constant over time but decreased at the beginning of rainfall events, indicating large spatial differences in groundwater responses, and increased after peak flow, when groundwater levels could be considered to be spatially in a steady state. Our findings indicate that topographic indices are useful to predict median groundwater levels in catchments with low-permeability soils and that the TWI assumptions are best met when groundwater levels change slowly.

DOI: https://doi.org/10.1002/2013WR015009

Originally published at:
Rinderer, Michael; van Meerveld, H J; Seibert, Jan (2014). Topographic controls on shallow groundwater levels in a steep, prealpine catchment: When are the TWI assumptions valid? Water Resources Research, 50(7):6067-6080.
DOI: https://doi.org/10.1002/2013WR015009

AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2013WR015009

Key Points:

- Median groundwater levels were correlated to topographic indices
- Correlation between groundwater levels and topographic indices varied over time
- TWI assumptions were most valid during wet conditions, after peak flows

Correspondence to:
M. Rinderer,
michael.rinderer@geo.uzh.ch

Citation:
Rinderer, M., H. J. van Meerveld, and J. Seibert (2014), Topographic controls on shallow groundwater levels in a steep, prealpine catchment: When are the TWI assumptions valid?, *Water Resour. Res.*, *50*, 6067–6080, doi:10.1002/2013WR015009.

Received 12 NOV 2013
Accepted 27 JUN 2014
Accepted article online 30 JUN 2014
Published online 23 JUL 2014

Topographic controls on shallow groundwater levels in a steep, prealpine catchment: When are the TWI assumptions valid?

M. Rinderer[1], H. J. van Meerveld[2], and J. Seibert[1,3,4]

[1]Department of Geography, University of Zurich, Zurich, Switzerland, [2]Critical Zone Hydrology Group, Faculty of Earth and Life Sciences, VU University Amsterdam, Amsterdam, Netherlands, [3]Department of Earth Sciences, Uppsala University, Uppsala, Sweden, [4]Department of Physical Geography and Quaternary Geology, Stockholm University, Stockholm, Sweden

Abstract Topographic indices like the Topographic Wetness Index (TWI) have been used to predict spatial patterns of average groundwater levels and to model the dynamics of the saturated zone during events (e.g., TOPMODEL). However, the assumptions underlying the use of the TWI in hydrological models, of which the most important is that groundwater level variation can be approximated by a series of steady state situations, are rarely tested. It is also not clear how well findings from existing hillslope studies on sites with transmissive soil can be transferred to entire catchments with less permeable soils. This study, therefore, evaluated the suitability of selected topographic indices to describe spatial groundwater level variations based on time series from 51 groundwater wells in a 20 ha catchment with low-permeability soils in Switzerland. Results showed that median groundwater levels were correlated to slope, curvature, and TWI, but the strength of correlation depended on whether the indices characterized the local topography or the topography of the upslope contributing area. The correlation between TWI and groundwater levels was not constant over time but decreased at the beginning of rainfall events, indicating large spatial differences in groundwater responses, and increased after peak flow, when groundwater levels could be considered to be spatially in a steady state. Our findings indicate that topographic indices are useful to predict median groundwater levels in catchments with low-permeability soils and that the TWI assumptions are best met when groundwater levels change slowly.

1. Introduction

The spatio-temporal variation in groundwater levels and, thus, groundwater storage within a catchment significantly influences catchment runoff response [*McGlynn et al.*, 2004; *Zehe et al.*, 2005; *Spence et al.*, 2009]. Temporal differences in the area where groundwater storage capacity is exceeded as a result of rainfall or snowmelt govern the changing patterns of runoff source areas and overland flow connectivity, as described in the variable source area concept [*Hewlett and Hibbert*, 1967; *Ambroise*, 2004; *Gomi et al.*, 2008]. Similarly, perched groundwater levels on hillslopes determine the activation of subsurface flow pathways. When these pathways become hydrologically connected to the stream network, this can result in a rapid increase in runoff [*Spence and Woo*, 2006; *Tromp-van Meerveld and McDonnell*, 2006; *Laudon et al.*, 2007; *Lehmann et al.*, 2007]. While temporal differences in groundwater levels are important for understanding runoff processes during rainfall events, average groundwater conditions can serve as an indicator of typical wetness conditions in a catchment and its average storage capacity. As continuous groundwater level monitoring is restricted to selected sites, understanding the processes and controlling factors that lead to spatial variability in groundwater levels in a catchment is important. Quantifying relations between groundwater levels and site characteristics, such as the topographic characteristics of the monitoring site and its upslope contributing area, soil and bedrock properties, and vegetation, enables the prediction of groundwater levels at unmonitored sites. This is a prerequisite for identifying spatial patterns of groundwater above an impeding soil or bedrock layer and its spatial connection, especially to the stream network.

Several studies have demonstrated that surface and subsurface topography, vegetation, soil- and bedrock properties control the spatial variability in groundwater levels. As groundwater levels are the result of local drainage, local recharge from infiltration, and groundwater input from upslope, it is necessary to differentiate between characteristics of the monitoring site itself (local controls) and those that are representative of the upslope contributing area (upslope controls). In mountain catchments with often shallow soils and groundwater tables, topography is assumed to be a major driver of spatial differences in groundwater levels as the gravitational potential is a dominant part of the total potential [*Anderson and Burt*, 1978]. This important role of topography was recognized early and forms the basis of several conceptual hydrological models, such as TOPMODEL [*Beven and Kirkby*, 1979] and TOPOG [*O'Loughlin*, 1986].

Many of the topography-based, hydrological models assume that sites with the same Topographic Wetness Index (TWI; $\ln(a/\tan\beta)$, where a is the upslope contributing area per unit contour length (m) and β is the local slope ($^\circ$)), have a similar groundwater response. This consideration is based on the assumptions that the local slope is a proxy of the local hydraulic gradient and that the whole upslope contributing area contributes to groundwater flow toward the site [*Beven and Kirkby*, 1979]. Furthermore, it is assumed that spatial groundwater table variations can be approximated by successions of steady state situations, implying for each point in time an equilibrium between inflow from the upslope contributing area and local drainage everywhere in the catchment. This implies a spatially persistent pattern of groundwater levels in a catchment. In the following, we refer to these assumptions as the *TWI assumptions*.

With the growing popularity of the TOPMODEL concept in the 1980s and 1990s, a series of studies investigated the relations between topographic indices, especially the TWI, and groundwater levels. A good agreement was found in some studies, mainly during wet conditions [*Anderson and Burt*, 1978; *Burt and Butcher*, 1985] and for sites with shallow groundwater tables [*Troch et al*., 1993], whereas other studies reported poorer agreements, which could partly be attributed to flat terrain [*Barling et al*., 1994] or transmissive soils [*Seibert et al*., 1997]. Some studies restricted monitoring to near-stream and footslope locations and measured groundwater levels at a coarse temporal resolution, which may also have contributed to the contradictory findings [*Moore and Thompson*, 1996; *Buttle et al*., 2001].

Distinct differences in the groundwater response have been observed for wells in the riparian zone and the upper hillslope zone [*Seibert et al*., 2003; *Haught and van Meerveld*, 2011]. While water levels in riparian wells were well correlated with streamflow in these studies, they were not for the upland sites. In other studies, water levels increased earlier in upland wells than in footslope sites due to differences in surface and bedrock topography or soil depth [*Tromp-van Meerveld and McDonnell*, 2006; *Rodhe and Seibert*, 2011; *Penna et al*., 2014]. These differences in groundwater response might partly explain why modeled groundwater levels did not agree with observations, when using TWI-based models or TWI as an external drift function for interpolating groundwater table elevations [*Seibert et al*., 1997; *Desbarats et al*., 2002].

The site characteristics that are most strongly correlated to groundwater levels and therefore are considered to control groundwater levels have been investigated only in a few studies. Individual Spearman rank correlation analysis showed that mean relative groundwater levels were correlated to land use classes, soil properties, local slope, hillslope position, and well depth, but not upslope contributing area, local plan and local profile curvature, saturated hydraulic conductivity, and vegetation properties for hillslopes in southern Germany with sandy loam textured soils [*Bachmair and Weiler*, 2012]. However, when applying a nonparametric multivariate technique (random forest approach [*Breiman*, 2001]) to predict the mean relative groundwater levels using the same independent variables as listed above, saturated hydraulic conductivity and local profile curvature were the most importance predictors, followed by topographic variables such as local slope, local plan curvature, and upslope contributing area. The explained variance of mean relative groundwater levels using the random forest approach was only 30%.

Bachmair and Weiler [2012] present the only study that reported seasonal differences in the importance of site characteristics on groundwater levels. They found that correlations between mean water tables and site characteristics were lower during summer than during fall, winter and spring. Correlations between mean groundwater levels with site characteristics were even lower for individual events [*Bachmair and Weiler*, 2012]. We are not aware of any previous study that investigated the change in correlation between groundwater levels and site characteristics during events. This is maybe partly because, until recently, continuous measurements of groundwater levels at many points in a catchment were not feasible. As the groundwater response is known to vary throughout a catchment during a rainfall event and patterns in groundwater

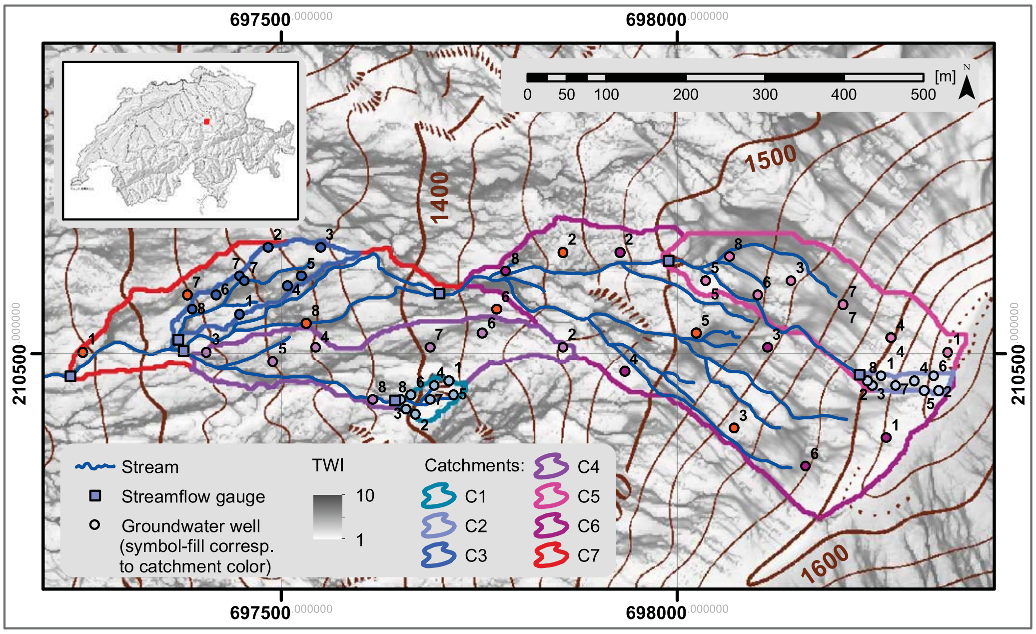

Figure 1. The study catchment showing the seven nested subcatchments with a streamflow gauging station at each outlet, the location of the spatially distributed groundwater wells (numbered from 1 to 8 in the order of increasing wetness in each subcatchment), and Topographic Wetness Index in the background (topographic map: reproduced under permission of swisstopo (BA12059)).

levels, therefore, change over time, a temporal change in the correlation between groundwater levels and topographic indices is likely.

Previous studies have investigated groundwater dynamics and key controls mainly on hillslopes or at the riparian-hillslope interface, but less is known about catchment-wide variability in groundwater levels. Furthermore, most of the previous studies have been conducted at sites with transmissive soils [*Seibert et al*., 2003; *Tromp-van Meerveld and McDonnell*, 2006; *Detty and McGuire*, 2010]. The dominant processes and catchment characteristics (e.g., soil properties, topography) that determine groundwater dynamics are expected to be different in catchments with less permeable soils (e.g., Gleysols) because groundwater levels are expected to be more persistent, quicker to respond, and more frequent, because of the lower storage deficit and smaller drainable porosity compared to catchments with transmissive soils.

This study, therefore, aimed to assess the influence of topographic characteristics on groundwater levels in a steep headwater catchment with low-permeability soils by addressing the following questions:

1. To what extent does topography control median groundwater levels in a catchment with low-permeability soils?

2. Are there differences in the correlation of median groundwater levels with local and upslope topographic characteristics?

3. Does the correlation between topography and groundwater levels vary over time?

2. Methods

2.1. Site Description

The 20 ha headwater study catchment is located in the Alptal, a pre-alpine valley about 40 km southeast of Zurich, Switzerland (Figure 1). The Alptal region and particularly the Erlenbach catchment is known for a long history of research on the influence of forests on runoff, water quality, and bedload transport [*Hegg et al*., 2006]. However, the Erlenbach catchment was not chosen for this study because it is affected by anthropogenic drainage. Instead a 20 ha neighboring catchment was investigated. Mean annual precipitation is 2300 mm/yr, of which about 30% falls as snow, and is evenly distributed throughout the year [*Feyen et al*., 1999]. The catchment extends from 1270 m asl. to 1650 m asl. and has an average slope of 35%.

Landslides and soil creep have developed a sequence of steeper and flatter landscape units, each with complex microtopography, and a dense natural drainage network (205 m/ha) with most channels not being deeply incised, except for the main channel close to the catchment outlet. Moor landscapes and wet grassland areas have formed in flat or concave parts of the catchment (ca. 7 ha), while steeper slopes and ridge sites have open coniferous forest stands (*Picea abies L*. with an understory of *Vaccinium* sp.) [*Hagedorn et al*., 2000] (ca. 11 ha). Parts of the upper catchment (ca. 2 ha) are used for cattle grazing during summer (area based on aerial photographs from 2007). The spatial distribution of soil types and soil depth are related to differences in local topography. In wet depressions (mainly grassland), where the water table is persistently close to the soil surface, a mollic Gleysol with a topsoil high in carbonate can be found. The mineral soil consists of a permanently reduced Bg horizon, with typically 43% clay, 42% silt, and 15% sand [*Schleppi et al*., 1998]. At the ridge sites, where the water table is normally more than 40 cm below the soil surface, trees grow on an umbric Gleysol with an oxidized Bw horizon (49% clay, 46% silt, and 5% sand) [*Schleppi et al*., 1998; *Hagedorn et al*., 2001] with macropores. Soil depth varies between 0.5 m at ridges to more than 2.5 m in depressions. The bedrock consists of a poorly permeable clay-rich Flysch with calcareous sandstone and argillite and bentonite schist layers [*Mohn et al*., 2000].

2.2. Monitoring Network and Measurements

The study catchment consists of seven nested subcatchments (C1–C7) of varying size ($\sim$0.2, $\sim$1, $\sim$3.5, $\sim$12 to 20 ha; see Figure 1). In contrast to most previous studies, where groundwater levels were measured along transects or on a single hillslope, the monitoring network of this study was designed to provide a good spatial coverage and to capture wet and dry sites within each subcatchment. As field observations suggested that TWI might be a good indicator of soil wetness, TWI (calculation described in section 2.3) was used to determine the locations of the monitoring sites. For each subcatchment, the pixels were grouped into eight TWI classes with equal frequency. The coordinates of the monitoring sites were determined by selecting the pixels with a TWI similar to the median TWI of each class. As the subcatchments were nested, five monitoring sites overlapped, resulting in 51 monitoring sites with continuous groundwater level observations (Figure 1). The monitoring sites included 8 ridge site, 22 midslope, and 21 footslope or depression sites. Of the 51 monitoring sites, 25 had a mollic Gleysol and 26 had an umbric Gleysol profile; 20 sites were forested and 31 were located in grassland. Soil depth was not statistically significantly different between mollic and umbric Gleysol monitoring locations (Mann-Whitney $U = 288$, $p = 0.5$). Soil depth was correlated to the local slope (Spearman rank correlation coefficient $r_s = -0.44$, $p = 0.001$).

All boreholes were hand-augered down to the parent material. The mean depth was 1.06 m (min: 0.46 m, max: 2.16 m). The wells consist of a PVC pipe of 4 cm diameter, screened over the full length up to 10 cm below the surface; the borehole was backfilled with coarse filter sand after installation of the pipe. To prevent water entering the well and auger hole from the soil surface, the filter pack was sealed with bentonite and plastic foil 5–10 cm below the soil surface. Water levels were measured in the wells between September 2010 and November 2012 using Odyssey capacitance water level loggers (Dataflow Systems Pty Limited). The measurement interval was 5 min during summer (May until December) and 10 min during winter. Groundwater level data were checked with manual water level measurements when downloading the data, every 2–3 months. Saturated hydraulic conductivity of the mineral soil layer was determined by the *Bouwer and Rice* [1976] method based on at least three slug and bail tests at each groundwater-monitoring site during summer 2012.

Stream stage was measured every 5 min at each of the seven subcatchments during summer (May until December) 2011 and 2012 using pressure loggers (DL/N 70 by STS, Sensor Technik Sirnach AG) and every 10 min during winter 2011 and 2012 using capacitance water level loggers (Odyssey). HS flumes (subcatchment C1 and C2) and 90° V notch weirs (subcatchments C3, C4, and C5) were used in channels with moderate sediment transport. Stage was converted into streamflow using rating curves [*U.S. Department of the Interior*, 2001] that were checked by repeated salt dilution measurements during seven events of different magnitude and a low-flow period. For the largest and second largest catchments (C6 and C7), stage was recorded in a natural cross section as weir construction was not possible. Changes in the natural cross section were documented monthly and deemed to be minor for the study period. Salt dilution was used to determine the rating curves for these cross sections.

Precipitation, air temperature, and barometric pressure were measured at a permanent meteorological weather station 1 km from the experimental catchment at 1219 m asl. Precipitation and air temperature

10.1002/2013WR015009

Table 1. Spearman Rank Correlation Coefficients (r_s) for the Relations Between Median (Relative and Absolute) Groundwater (GW) Levels and Selected Local and Upslope Topographic Site Characteristics[a]

Site Characteristic	Method/Reference	Units	Type	r_s (Median Relative GW Level)	r_s (Median Absolute GW Level)
Local slope	Calculated based on the D∞ flow algorithm [*Tarborton*, 1997]	%	Local	**−0.67**	−0.57
Mean slope of upslope contribution area	Upslope contributing area determined by the MD∞ flow algorithm [*Seibert and McGlynn*, 2007]	%	Upslope	−0.23	−0.15
Local curvature	Second derivative of a bivariate quadratic surface through a local 3 × 3 kernal [*Travis et al.*, 1975; *Evans*, 1980]	-	Local	−0.23	−0.26
Mean curvature of upslope contribution area	Upslope contributing area determined by the MD∞ flow algorithm [*Seibert and McGlynn*, 2007]	-	Upslope	**−0.80**	**−0.77**
Upslope contributing area	Determined by the MD∞ method [*Seibert and McGlynn*, 2007]	m^2	Upslope	**0.69**	**0.70**
Topographic wetness index (TWI)	ln(a/tanβ) [*Beven and Kirkby*, 1979]	ln(m)	Upslope	**0.78**	**0.77**
Mean TWI of upslope contribution area	Upslope contributing area determined by the MD∞ flow algorithm [*Seibert and McGlynn*, 2007]	ln(m)	Upslope	**0.62**	**0.61**

[a]Bold: r_s statistically significant with $p < 0.05$; data: September 2010 to November 2012.

were measured every 10 min, while barometric pressure was measured every 5 min. There is no reliable information on the spatial patterns of precipitation in the catchment, but we expect the altitudinal gradient in precipitation to be small and differences in the timing of the onset of precipitation to even out over the study period of 27 months.

2.3. Site Characteristics

We defined *key controls* as the characteristics that are significantly correlated to the median values of the groundwater level time series of all sites and therefore can explain parts of the observed spatial variability in median groundwater levels across the catchment. As we expected differences in the importance of local characteristics of a site and the characteristics of its upslope contributing area, we defined *local controls* as properties that characterize the monitoring site itself and *upslope controls* as the properties that characterize the upslope contributing area. The site characteristics selected for this study were local slope, local curvature, TWI, upslope contributing area, mean slope, mean curvature, and mean TWI of the upslope contributing area (Table 1).

The topographic site characteristics were calculated based on a Digital Terrain Model (DTM) derived from LiDAR. DEM resolutions of 2, 4, 6, 8, and 10 m were tested, and 6 m was found to be the optimum for capturing the prominent morphologic features (ridges and depressions) without being obscured by microtopography. For all upslope characteristics, the triangular multiple flow direction algorithm [*Seibert and McGlynn*, 2007] was used for downslope routing of the accumulated area. All indices were calculated using the open source software SAGA-GIS [*Conrad*, 2007]. The mean values of the tested topographic indices for the upslope contributing area might not be representative if they are based only on a few pixels, but we consider this effect to be minor because the correlations between upslope controls and median groundwater levels were similar when sites with an upslope contributing area smaller than 125 m^2 (lower 25% quantile; equivalent to ca. 3 pixels) were excluded.

2.4. Analytical Methods

To quantify the relation between the topographic characteristics and groundwater levels, the Spearman rank correlation coefficient (r_s) was determined [*Spearman*, 1904]. For characterizing the average system state, we chose median instead of mean groundwater levels since these are less influenced by extremes and more robust for censored data (i.e., when the groundwater level falls below the bottom of the groundwater well). As soil depth and, thus, well depth differed between sites, groundwater levels were scaled by the soil depth (1 = water level at the soil surface, 0 = dry well). We refer to these scaled water levels as *relative groundwater levels* throughout the remainder of this text, whereas the unscaled water levels are referred

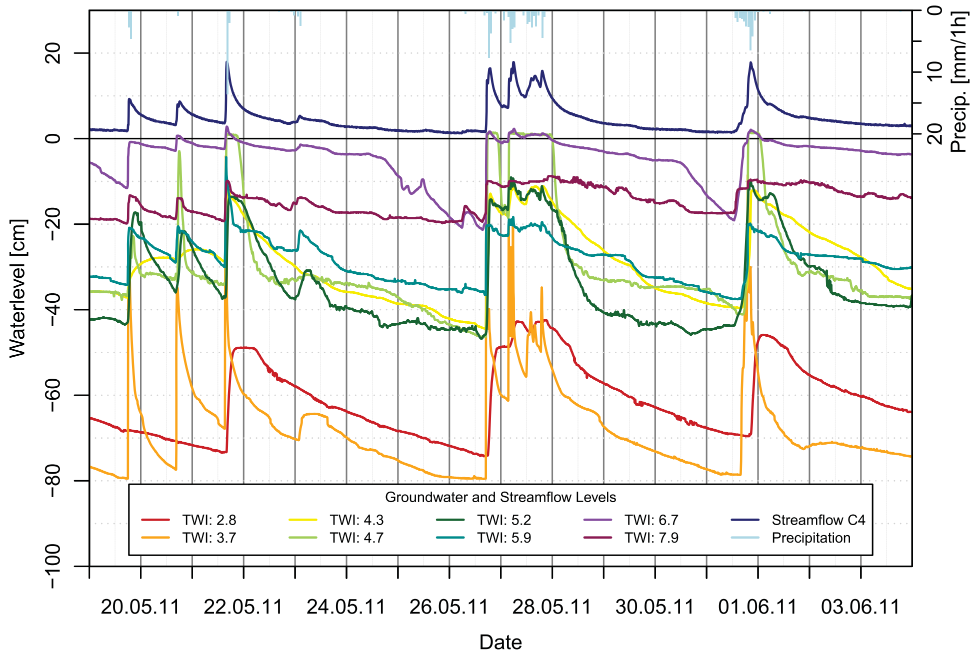

Figure 2. Groundwater dynamics of eight, representative wells with a different Topographic Wetness Index (TWI) showing distinct differences in response, peak groundwater level and recession, together with stream stage in catchment C4. Note: groundwater levels are given in cm (negative values indicate distance below the surface).

to as *absolute groundwater levels*. The software R (version 2.14.1) was used to analyze the data [*R Development Core Team*, 2005]. A statistical significance level of $\alpha = 0.05$ was applied throughout the study.

The continuous measurement of groundwater levels also allowed the investigation of the temporal variation in the correlation between groundwater levels and TWI. Groundwater levels and streamflow data were aggregated to hourly time steps by calculating the mean to remove noise in the data. Rank correlation coefficients between groundwater levels and TWI were then calculated for each hour and related to streamflow and the relative change in streamflow (dQ/Q) in subcatchment C5. Streamflow was assumed to be an indicator of the system state, and C5 was used because it provided the most complete runoff series. Data points were further classified according to three hydrologically relevant seasons in the Alptal region: the *growing season* from the beginning of June until the end of September with frequent rainfall events, the *dormant season* between the beginning of October and the end of January and *spring*, including snowmelt between the beginning of February and the end of May.

3. Results

3.1. Characterizing Groundwater Variability

Groundwater dynamics varied spatially across the small mountain headwater catchment (Figure 2). Most sites with a TWI $<$ 4 did not respond during every rainfall event and seemed to have a threshold type of response behavior. Most other sites responded during the majority of the rainfall events but differed in their peak groundwater level. There was also a difference in the lag time between the start of a rainfall event and the rise of the groundwater level. For some sites, the recession limb was almost as steep as the rising limb, while for others, it took several days to return to the base level. Even for sites with a similar rate of recession, the median absolute groundwater level was distinctly different. Despite differences in the groundwater hydrographs of individual sites, similarities could be identified. Sites with a TWI $>$ 6 responded faster than sites with a TWI $<$ 4. For most sites with a TWI $>$ 6, the groundwater levels were close to the soil surface most of the time, the rise during an event was small compared to other sites, and the groundwater levels tended to remain elevated for several days after rainfall events. Sites with a TWI between 4 and 6 showed the highest response frequency and amplitude and differed most in mean groundwater levels, while sites with a TWI $<$ 4 only responded to large rainfall events or events with a high rainfall intensity.

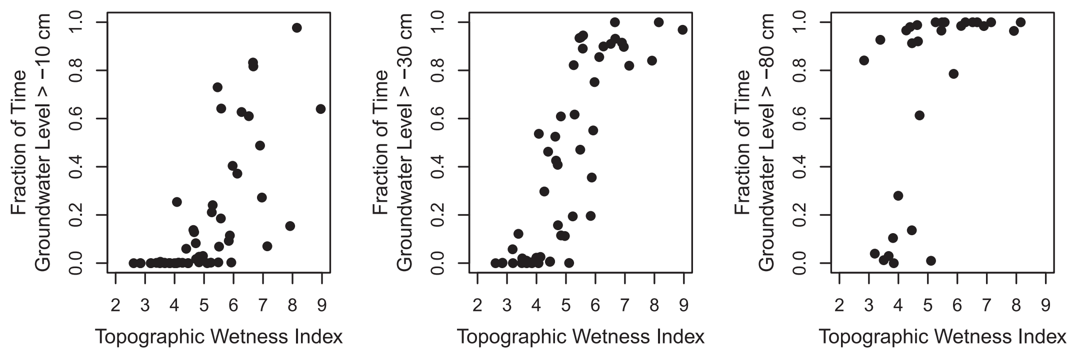

Figure 3. Fraction of time the groundwater level at each site was within (left) 10 cm, (middle) 30 cm, or (right) 80 cm from the soil surface as a function of Topographic Wetness Index (TWI, ln(m)).

The skewness of the frequency distributions of the groundwater levels characterizes the water table dynamics at each site. Sites with a TWI < 4 had predominantly positively skewed frequency distributions (i.e., mainly low water levels), while sites with a TWI > 6 were predominantly negatively skewed (i.e., mainly high water levels). The groundwater level distributions of sites with a local slope $<30\%$ were predominantly negatively skewed, while for sites with a local slope $>50\%$ they were predominantly positively skewed. The skewness of the groundwater frequency distribution was correlated to all topographic indices considered in this study (e.g., local slope: $r_s = 0.68$, TWI: $r_s = -0.69$), except local curvature. The fraction of time the wells were filled to a certain level below the soil surface was also related to topography. For sites with a TWI < 4, groundwater levels were almost never within 10 cm from the surface, whereas for sites with a TWI > 4 there was considerable spread and a weak tendency of an increasing fraction of time with water levels within 10 cm from the soil surface, with increasing TWI (Figure 3, left). This relation was more pronounced when analyzing the fraction of time that water levels were within 30 cm from the soil surface, especially for sites with a TWI between 4 and 6 (Figure 3, middle). Only sites with a TWI > 7 almost always had a water level within 30 cm from the surface. A similar pattern could be observed for the fraction of time water levels were within 50 cm from the soil surface (not shown). All sites had a water level within 80 cm from the surface for $>80\%$ of the time, except for nine sites with a TWI < 5 (Figure 3, right).

3.2. Correlation Analysis

The median relative groundwater levels were correlated to most of the selected topographic indices. However, the strength of the correlation differed for the local and upslope topographic characteristics. The median groundwater levels were correlated to the local slope ($r_s = -0.67$) but not to the mean slope of the upslope contributing area (Figures 4a and 4b and Table 1). Steeper sites generally had lower median relative groundwater levels. While sites with a local slope between 30 and 50% had median relative groundwater levels over almost the entire range (between 0.05 and 0.9), flatter and steeper sites had median relative groundwater levels >0.6 and <0.3, respectively. These results were similar for the median absolute groundwater levels, but the correlation coefficients were lower (Table 1).

In contrast to slope, the median relative groundwater levels were highly correlated to the mean curvature of the upslope contributing area ($r_s = -0.80$) but not to the local curvature (Figures 4c and 4d and Table 1). Most sites had a local curvature between -0.5 and 0.5, but regardless of being convex or concave, the median relative groundwater levels ranged between 0 and 1 (Figure 4c). The correlations were similar for the median absolute groundwater levels (Table 1).

The median relative groundwater levels were also correlated to the upslope contributing area ($r_s = 0.69$) (see Figures 4e and Table 1). For the majority of sites with an upslope contributing area smaller than about 200 m^2, the median relative groundwater level was less than 0.3, except for five sites that had median relative groundwater levels between 0.4 and 0.7. For sites with an upslope contributing area between 200 and 600 m^2, the median relative groundwater levels varied over the entire range. For sites with an upslope contributing area larger than 600 m^2, median relative groundwater levels were higher than 0.7. The upslope contributing area was similarly correlated to the median absolute groundwater levels ($r_s = 0.70$).

10.1002/2013WR015009

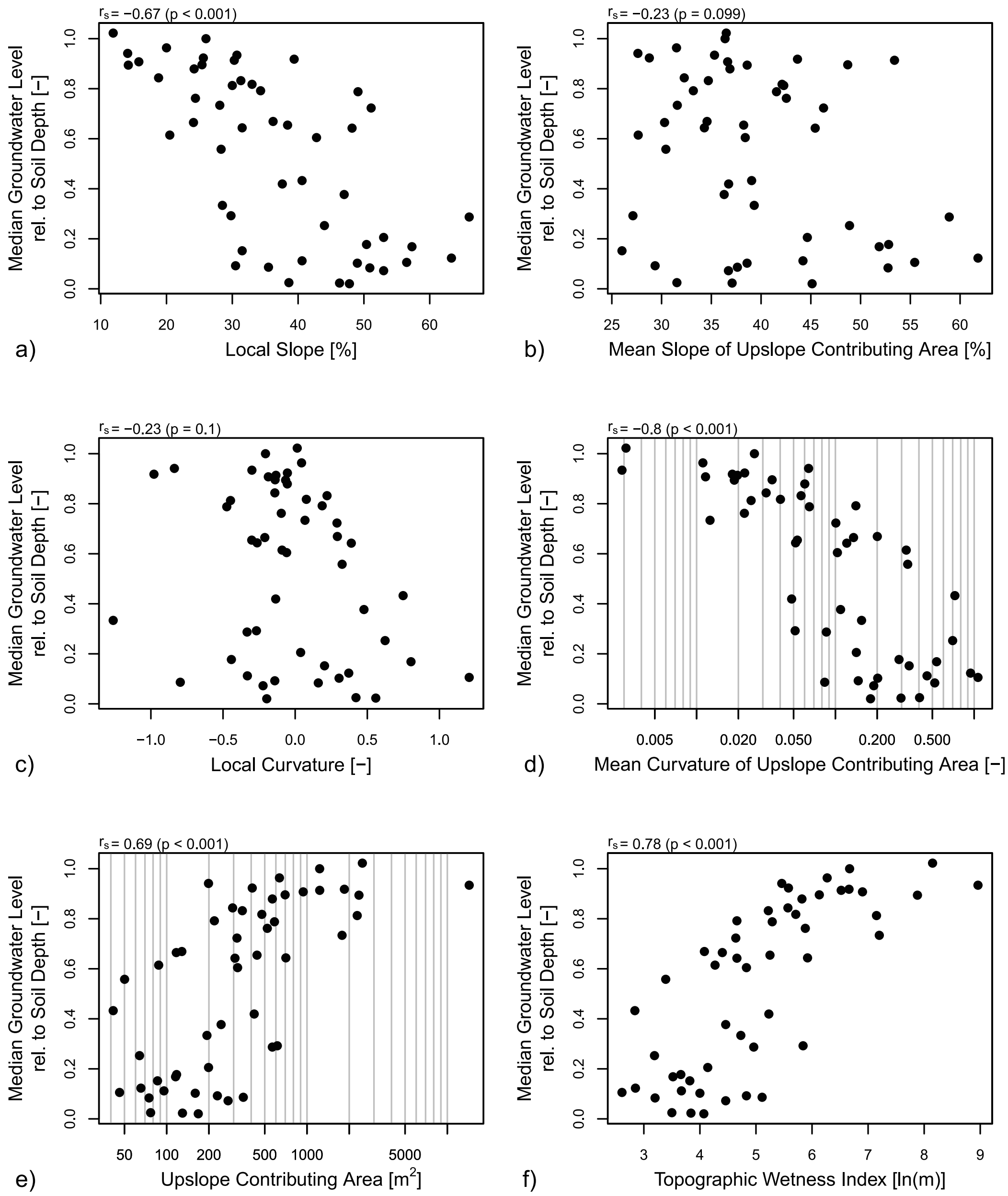

Figure 4. Median groundwater levels relative to soil depth (1 = at the soil surface, 0 = at bottom of the well) as a function of (a) local slope, (b) mean slope of the upslope contributing area, (c) local curvature, (d) mean curvature of the upslope contributing area, (e) upslope contributing area, and (f) Topographic Wetness Index.

The median relative groundwater levels increased linearly with TWI ($r_s = 0.78$) but were highly variable for sites with a TWI between 4 and 6 (Figure 4f and Table 1). Sites with a TWI > 6 had a median relative groundwater level of 0.7 or higher. The median relative groundwater levels were also correlated to the mean TWI of the upslope contributing area, but the correlation coefficient was lower ($r_s = 0.62$). The correlations were similar for the median absolute groundwater levels (Table 1).

We also considered the soil depth and the saturated hydraulic conductivity of the mineral soil to be important controls on median groundwater levels, but the correlations were not statistically significant. The spatial distribution of soil type and vegetation within the study catchment was related to the median groundwater levels (*p* value of Mann-Whitney test < 0.001) and could be predicted by topographic position, e.g., footslopes or depressions had predominantly mollic Gleysols and grassland vegetation, whereas ridge

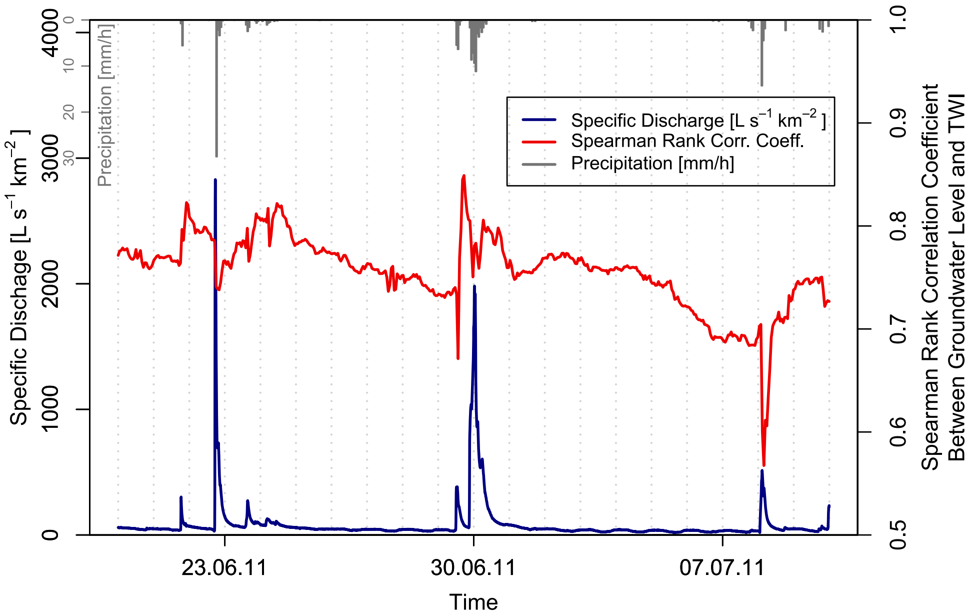

Figure 5. Example of a time series of the Spearman rank correlation coefficients (r_s) between groundwater levels at 51 locations and the Topographic Wetness Index (TWI) (red line). Precipitation and specific discharge at subcatchment C5 are shown in gray and blue, respectively.

sites had predominantly umbric Gleysols and were often forested (Pearson's chi-square test, $p < 0.001$ (soil type), and $p < 0.003$ (vegetation); Cramer's V value, a measure of the strength of correlation, was 0.51 (soil type) and 0.33 (vegetation)).

3.3. Changes in the Correlation Between Groundwater Level Patterns and TWI Over Time

The continuous groundwater measurements allowed quantification of the temporal variation in the correlation between groundwater levels and topographic indices. The correlation between TWI and absolute groundwater levels decreased strongly at the beginning of rainfall events and reached the lowest values shortly after peak streamflow (Figure 5). During the falling limb of the hydrograph, r_s increased quickly and reached the highest values 12 h–2 days after the event. During dry periods, r_s gradually decreased until the beginning of the next event. The drop in correlation at the beginning of a rainfall event was particularly large after long, dry periods.

This event-scale change in correlation persisted throughout the year but was superimposed on a seasonal cycle (Figure 6): r_s was highest during spring, with values ranging between 0.75 and 0.85. Streamflow was never below 40 L s^{-1} km^{-2} during spring. The lowest r_s of 0.5–0.6 occurred during the dormant season, in particular when streamflow was below 10 L s^{-1} km^{-2}. This streamflow was exceeded during 87% of time during the 27 month study period. During the growing season, the correlation between groundwater levels and TWI varied between 0.65 and 0.75 during low ($<$10 L s^{-1} km^{-2}) and high ($>$100 L s^{-1} km^{-2}) streamflow conditions. These discharge values were exceeded during 87% and 13% of the study period, respectively. The maximum r_s of up to 0.80 occurred during intermediate streamflow conditions (10–100 L s^{-1} km^{-2}; median streamflow: 28 L s^{-1} km^{-2}).

The wide range of streamflow conditions for which r_s values were higher than 0.7 suggested that it was not the event magnitude but rather conditions with small changes in runoff and, thus, also groundwater levels for which r_s values were highest. Under these conditions, the assumption of groundwater levels following a succession of steady state situations might have been fulfilled best. A bell-shaped relation with highest r_s values at near-zero dQ/Q (Figure 7) was pronounced for all streamflow conditions although for the smallest streamflow class ($<$12.5 L s^{-1} km^{-2}) it was least pronounced (see Figure 7, inset). Most of the low Spearman rank correlation coefficients in this class occurred during the dormant season, which is in agreement with the results shown in Figure 6.

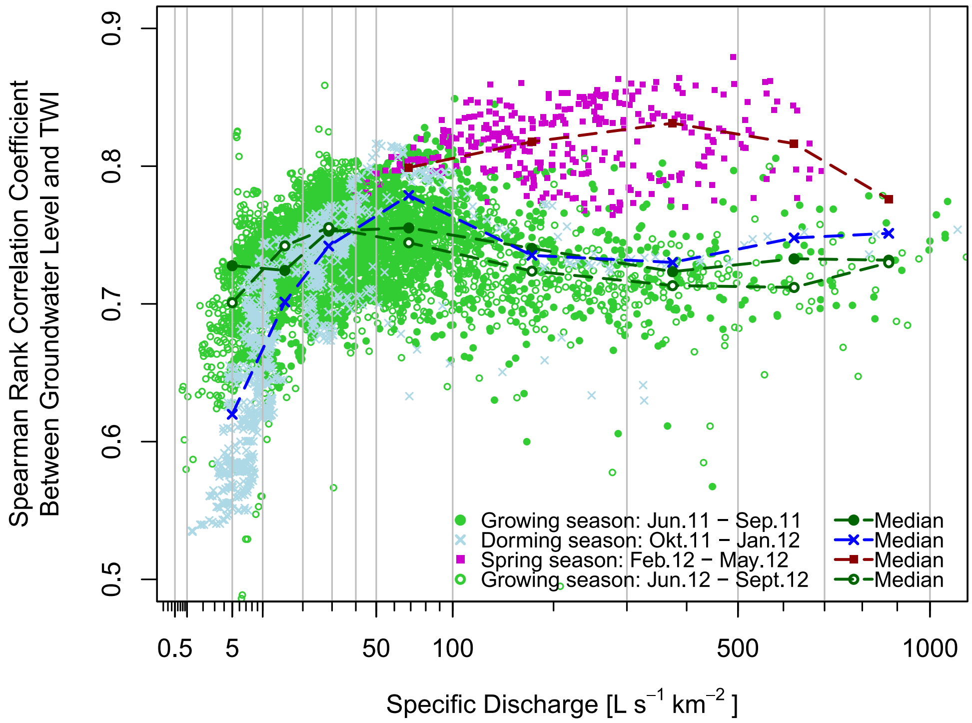

Figure 6. Spearman rank correlation coefficients (r_s) between groundwater level and Topographic Wetness Index (TWI) plotted as a function of specific discharge as an indicator of the average catchment state. Discharge from subcatchment C5 was chosen because it has the longest data series. The different colors and symbols indicate the different seasons. The median curves for defined streamflow classes are shown in darker dashed lines.

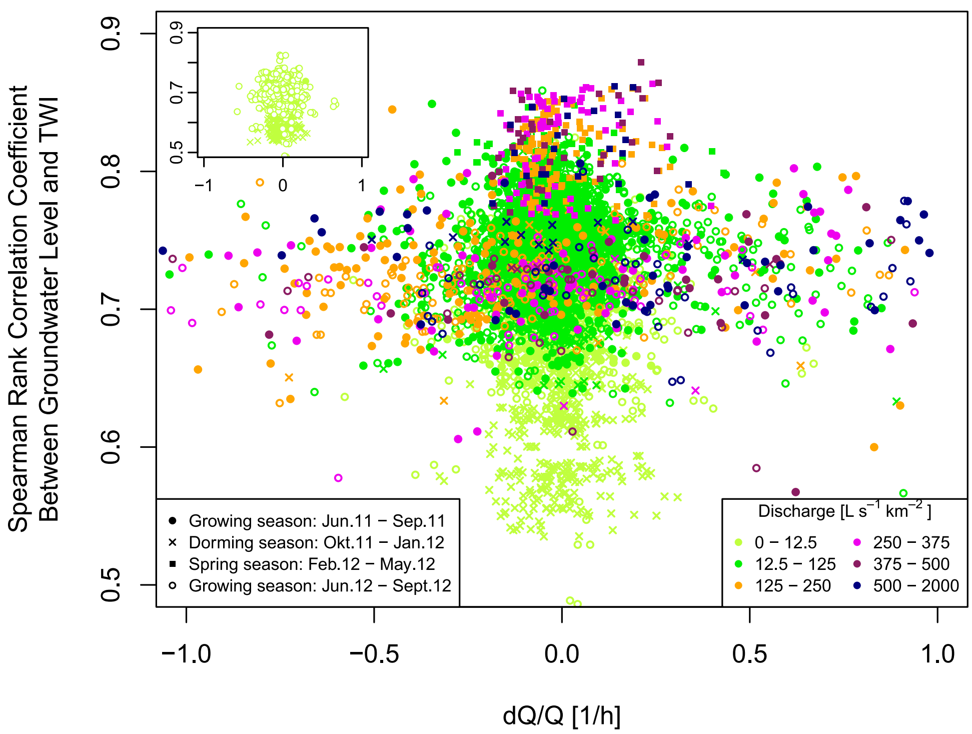

Figure 7. Spearman rank correlation coefficients (r_s) between groundwater level and Topographic Wetness Index (TWI) plotted as a function of the relative change in streamflow at subcatchment C5. Symbols represent different seasons, while colors represent different streamflow classes. The inset in the upper left corner shows the data for streamflow < 12.5 L s^{-1} km^{-2} without overlap of the other streamflow classes.

10.1002/2013WR015009

4. Discussion

4.1. The Role of Topography on Groundwater Levels

The statistical significance and strength of the correlation ($r_s > 0.6$) suggest that topography exerts a significant control on the median groundwater levels in mountain catchments with low-permeability soils. Median groundwater levels were related to local controls, such as the local slope and the soil wetness (as described by the TWI), and upslope controls, such as the runoff concentration within the upslope contributing area (as described by the mean upslope curvature), subsurface water input from upslope (as described by the upslope contributing area), and mean soil wetness in the source area (as described by the mean TWI of the upslope contributing area). Interestingly, the relative strength of slope and curvature in explaining the median groundwater levels depended on whether they were considered as local or upslope controls.

Other studies also reported groundwater levels to be correlated to TWI, although the correlation coefficients were lower than in our study [*Detty and McGuire*, 2010]. A possible explanation for the lower correlations might be the more permeable soils in these catchments, which might lead to deeper median groundwater levels that are less influenced by the surface topography [*Bachmair and Weiler*, 2012]. In other studies, particularly on footslopes and in catchments with a relatively flat topography or conductive soils, topography was not identified as a dominant control and the TWI was weakly correlated to spatial groundwater level variations [*Moore and Thompson*, 1996; *Seibert et al*., 1997]. This is plausible since in flatter sites the hydraulic gradient, subsurface flow concentration, and contribution from upslope areas are smaller and, therefore, other controls are more likely to dominate the variability in median groundwater levels.

Only a few other studies have commented on the correlation between groundwater levels and topographic controls other than TWI. *Bachmair and Weiler* [2012] reported a nonsignificant correlation between local plan- and profile curvature and mean relative groundwater levels but did not investigate curvature of the upslope contributing area. The local slope was among the predictor variables with the strongest correlation ($r_s = -0.36$) with mean relative groundwater levels, but the correlation was lower than in our study ($r_s = -0.69$). Other predictor variables with similar or slightly higher correlations were land use ($r_s = -0.42$) and saturated hydraulic conductivity ($r_s = -0.39$). *Bachmair and Weiler* [2012] concluded, based on the low correlation coefficients, that important predictor variables were missing in their analysis but that topography and soil properties were among the important controls on groundwater responses of the three experimental hillslopes with transmissive soils. This is noticeable as their experimental hillslopes were explicitly chosen to be relative planar. Soil depth and saturated hydraulic conductivity of the mineral soil were not correlated to median groundwater levels in this hillslope study.

The upslope contributing area exerts an important control on groundwater and subsurface flow. Previous studies in the Alptal concluded that these fluxes were important components of the hillslopes water balance [*Feyen et al*., 1996]. Subsurface runoff (364 mm) from a small 10 m^2 experimental plot with 80 cm deep PVC panels on the uphill side and a trench on the downhill side exceeded net precipitation (=128 mm precipitation minus 26 mm evapotranspiration) by more than 260 mm during an 11 day measurement campaign [*Feyen et al*., 1996]. While this example might be exceptional due to groundwater upwelling at that topographic location, it shows that subsurface water input from upslope areas can be substantial. *Bachmair and Weiler* [2012] reported upslope contributing area to be more important than vegetation and soil properties only when accounting for interactions between predictor variables but not in the partial correlation analysis. *Detty and McGuire* [2010] found upslope contributing area to be significantly related to catchment wide water table duration but not when the analysis was performed for individual landforms (footslope, midslope, shoulder) or well transects.

The fact that other studies reported a lower correlation between topography and groundwater levels suggests that the governing subsurface runoff processes may be different in contrasting catchments. In steep mountain headwater catchments with low-permeability soils (e.g., Gleysols), perched groundwater systems are expected to prevail. As groundwater levels are predominantly shallow, subsurface flow through conductive soil layers and/or preferential flow paths near the soil surface is likely an important flow component during events. The humid conditions, together with the low drainable porosity of the soil matrix, cause median groundwater levels to be persistently close to the soil surface, soil moisture to be high, and storage capacity to be low. Our results and field observations suggest that spatial variability in groundwater levels is driven by the input from upslope areas, which is influenced by subsurface flow concentration (convergent or divergent shallow flow pathways in the upslope contributing area of each site). The local hydraulic gradient exerts a control on the downslope drainage conditions, which, together with upslope soil water inputs, determine groundwater levels.

In terms of differences in the dominant controls on groundwater levels and runoff mechanisms in different catchments, it appears that saturation and subsequent lateral subsurface flow in transmissive soils occurs at deeper depth than in low-permeability soils. Therefore, soil properties, like the saturated hydraulic conductivity and soil depth, as well as topography and infiltrability of the bedrock surface or deep impeding soil layer, are expected to be of greater importance than in environments with low-permeability soils [*McDonnell*, 1990; *Uchida et al*., 2003; *Tromp-van Meerveld et al*., 2007].

4.2. Predictability of Median Groundwater Levels

Variability in median groundwater levels was largest for sites with a local slope between 30 and 50% (24 sites out of 51), an upslope contributing area between 200 and 600 m^2 (18 sites out of 51), and a TWI between 4 and 6 (27 sites out of 51). These criteria applied to relatively large parts of the catchment (49%, 32%, 49%, respectively), predominantly at midslope locations. Eleven out of the 51 sites fulfilled all three criteria; two of them were among the most responsive sites in the catchment with the largest groundwater amplitude. The median groundwater levels were not statistically significantly different for the umbric and mollic Gleysols (Mann-Whitney test, $p > 0.28$), which suggests that soil type did not cause the large variability in median groundwater levels in this zone. Flatter footslopes and steeper ridge sites were characterized by a smaller variability in median groundwater levels. It could be speculated that a more complex and, therefore, more variable interplay of several, well-correlated controls dominate median groundwater levels on the midslopes, while for the footslopes and ridges only a few important factors determine the balance between subsurface input from upslope and drainage. This makes prediction of median groundwater levels in footslope and ridge sites more reliable than for midslopes and suggests that midslopes are most relevant in terms of monitoring changes in groundwater storage and hydrological connectivity.

4.3. TWI Assumptions Evaluated by the Temporal Variability of Correlation Strength

The spatial groundwater level pattern did not maintain a persistent shape that shifted uniformly up and down in response to changes in saturated zone storage as assumed by the physical motivation of using TWI for modeling groundwater levels or streamflow. Instead the spatial pattern in groundwater levels changed during events and seasonally. We hypothesize that temporal differences in rainfall inputs and spatio-temporal differences in soil water storage cause differences in groundwater responses throughout the catchment during a rainfall event. While we expect parts of the catchment to be hydrologically disconnected prior to events or during dry periods, we assume large parts of the upslope contributing area to be connected during events (see TWI assumptions). In these situations, water tables are high and the local slope is a good predictor of the hydraulic gradient. During recession, groundwater levels slowly decline and the assumption of a succession of steady state conditions is more realistic, which was also indicated by stronger correlations during these periods. Toward the end of the recession period, parts of the upslope contributing area might become hydrologically disconnected. The longer the time that groundwater levels fall, the more heterogeneous they become throughout the catchment and the weaker the correlation with TWI becomes. Sites with a large upslope contributing area or low slope tend to have persistently high groundwater levels, while wells at other sites can fall dry.

The assumption of a persistent shape of the groundwater pattern that shifts uniformly up and down due to changes in saturated zone storage did hold neither for events nor for seasons. During the growing season, the groundwater pattern within the catchment varied because it was determined by differences in groundwater response during rainfall events. During the longer dry periods in late fall and winter, differences in groundwater levels were most pronounced. The TWI assumptions could be considered to be reasonably met only toward the end of the snowmelt season, when constant, low-intensity melt water inputs throughout large parts of the catchment caused groundwater levels to be high, and the upslope contributing area was, therefore, likely to be hydrologically connected (Figures 6 and 7).

More generally speaking, the assumption of steady state successions was best met during conditions of small changes in runoff (=near-zero dQ/Q) and presumably small changes in groundwater levels (Figure 7). The assumptions were, however, not fulfilled during large changes in groundwater levels and streamflow during the start of events, when spatial variability of rainfall inputs and subsurface flow from upslope areas, drainage, and associated delays were high. The saturated zone did also not respond in unison during the lowest flows at the end of long dry periods, when some wells were dry and connectivity was likely lowest. This was particularly pronounced during the long dry period in winter (see Figure 6, light blue data points, and Figure 7, light green data points).

5. Concluding Remarks

We found that topography is a good predictor of median groundwater levels in the studied mountain headwater catchment with low-permeability soils. Median groundwater levels were correlated with topographic indices and the strength of correlation differed depending on whether they were considered a local or an upslope topographic control. This suggests that groundwater levels were not only controlled by local drainage but also by subsurface inputs from upslope and that both scales (local and upslope contributing area) have to be considered to better understand the spatial variability in median groundwater levels.

This study also showed that the rank correlation between groundwater levels and TWI was not constant over time but decreased during rainfall events as differences in rainfall input and subsurface flow redistribution and associated delays led to spatial differences in groundwater responses. When groundwater levels were high and changed slowly, e.g., when the catchment was slowly draining after events or during snowmelt in spring, the TWI assumptions of steady state successions, connected upslope contributing areas, and surface slope as a proxy of the hydraulic gradient were fulfilled best. They were least appropriate during long dry periods, when parts of the catchment drained differently and became disconnected.

We expect our findings to also be applicable in other humid mountain headwater catchments with low-permeability soils and shallow groundwater tables as the topographic indices are proxies for generally applicable, physical properties and processes that seem to dominate in these catchments. Our study showed that the TWI assumptions might be useful simplifications for modeling applications in catchments with shallow groundwater levels during periods following rainfall events and during the snowmelt season when streamflow and groundwater levels change slowly. However, for modeling the groundwater response at the beginning of events and during long dry periods other modeling approaches are needed to better represent the saturated zone dynamics. This has implications for using TWI-based models to predict the spatial patterns of groundwater levels, their connectivity, and catchment runoff response.

Acknowledgments
The authors thank Manfred Stähli for helpful discussions and supply of meterological data, as well as Russell Smith and Dan Moore for valuable thoughts on the measurement concept and data analysis. Special thanks to Benjamin Fischer for sharing data, support and encouragement in the field, and numerous fruitful discussions. We thank the editor and the three reviewers for constructive comments on the manuscript, Tracy Ewen for proofreading Ellen Cerwinka, Jana Dusik, Seraina Kauer, Nadja Lavanga, Claudia Müller, Stephan Müller, Stefan Plötner, Sandra Pool, Paribesh Pradhan, Sandra Schärer, Karl Steiner, and Ivan Woodrich for field and laboratory assistance, Nans Addor for R tips, Volker Wichmann and Ronald Schmidt for SAGA and GIS data support, and the Swiss Federal Institute for Forest, Snow and Landscape Research WSL as well as OAK - Gemeinde Alpthal (canton Schwyz) for cooperation.

References

Ambroise, B. (2004), Variable''active'' versus ''contributing'' areas or periods: A necessary distinction, *Hydrol. Processes*, *18*(6), 1149–1155, doi:10.1002/hyp.5536.

Anderson, M. G., and T. P. Burt (1978), The role of topography in controlling throughflow generation, *Earth Surf. Processes*, *3*, 331–334.

Bachmair, S., and M. Weiler (2012), Hillslope characteristics as controls of subsurface flow variability, *Hydrol. Earth Syst. Sci.*, *16*(10), 3699–3715, doi:10.5194/hess-16-3699-2012.

Barling, R. D., W. Corporation, I. D. Moore, and B. Grayson (1994), A quasi dynamic wetness index for characterizing the spatial distribution of zones of surface saturation and soil water content, *Water Resour. Res.*, *30*(4), 1029–1044.

Beven, K. J., and M. J. Kirkby (1979), A physically based, variable contributing area model of basin hydrology, *Hydrol. Sci. Bull.*, *24*(1), 43–69.

Bouwer, H., and R. C. Rice (1976), A test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells, *Water Resour. Res.*, *12*(3), 423–428.

Breiman, L. E. O. (2001), Random forests, *Mach. Learing*, *45*, 5–32.

Burt, T. P., and D. P. Butcher (1985), Topographic controls of soil moisture distributions, *J. Soil Sci.*, *36*(1978), 469–486.

Buttle, J. M., P. W. Hazlett, C. D. Murray, I. F. Creed, D. S. Jeffries, and R. Semkin (2001), Prediction of groundwater characteristics in forested and harvested basins during spring snowmelt using a topographic index, *Hydrol. Processes*, *15*(18), 3389–3407, doi:10.1002/hyp.1033.

Conrad, O. (2007), Entwurf, Funktionsumfang, und Anwendung eines Systems für Automatisierte Geowissenscahftliche Analysen, PhD dissertation, 221 pp., Univ. of Göttingen, Göttingen, Germany.

Desbarats, A. J., C. E. Logan, M. J. Hinton, and D. R. Sharpe (2002), On the kriging of water table elevations using collateral information from a digital elevation model, *J. Hydrol.*, *255*(1–4), 25–38, doi:10.1016/S0022-1694(01)00504-2.

Detty, J. M., and K. J. McGuire (2010), Topographic controls on shallow groundwater dynamics: Implications of hydrologic connectivity between hillslopes and riparian zones in a till mantled catchment, *Hydrol. Processes*, *24*(16), 2222–2236, doi:10.1002/hyp.7656.

Evans, S. (1980), An integrated system of terrain analysis and slope mapping, *Z. Geomorphol.*, supplement, *36*, 274–294.

Feyen, H., J. Leuenberger, A. Papritz, M. Gysi, H. I. Fliihler, and P. Schleppi (1996), Runoff processes in catchments with a small scale topography, *Phys. Chem. Earth*, *21*(3), 177–181.

Feyen, H., H. Wunderli, H. Wydler, and A. Papritz (1999), A tracer experiment to study flow paths of water in a forest soil, *J. Hydrol.*, *225*(3–4), 155–167.

Gomi, T., R. C. Sidle, S. Miyata, K. Kosugi, and Y. Onda (2008), Dynamic runoff connectivity of overland flow on steep forested hillslopes: Scale effects and runoff transfer, *Water Resour. Res.*, *44*, W08411, doi:10.1029/2007WR005894.

Hagedorn, F., P. Schleppi, P. Waldner, and H. Flühler (2000), Export of dissolved organic carbon and nitrogen from Gleysol dominated catchments—The significance of water flow paths, *Biogeochemistry*, *50*, 137–161.

Hagedorn, F., P. Schleppi, J. Bucher, and H. Flühler (2001), Retention and leaching of elevated N deposition in a forest ecosystem with Gleysols, *Water Air Soil Pollut.*, *129*, 119–142.

Haught, D. R. W., and H. J. van Meerveld (2011), Spatial variation in transient water table responses: Differences between an upper and lower hillslope zone, *Hydrol. Processes*, *25*(25), 3866–3877, doi:10.1002/hyp.8354.

Hegg, C., B. W. McArdell, and A. Badoux (2006), One hundred years of mountain hydrology in Switzerland by the WSL, *Hydrol. Processes*, *20*(2), 371–376, doi:10.1002/hyp.6055.

Hewlett, J., and A. Hibbert (1967), Factors affecting the response of small watersheds to precipitation in humid areas, in *Proceedings of First International Symposium on Forest Hydrology*, vol. 33, edited by W. E. Sopper and H. W. Lull, pp. 275–290, Pergamon, Oxford.

Laudon, H., V. Sjoblom, I. Buffam, J. Seibert, and M. Morth (2007), The role of catchment scale and landscape characteristics for runoff generation of boreal streams, *J. Hydrol.*, *344*(3–4), 198–209, doi:10.1016/j.jhydrol.2007.07.010.

Lehmann, P., C. Hinz, G. McGrath, H. J. Tromp-van Meerveld, and J. J. McDonnell (2007), Rainfall threshold for hillslope outflow: An emergent property of flow pathway connectivity, *Hydrol. Earth Syst. Sci.*, *11*(2), 1047–1063.

McDonnell, J. J. (1990), A rationale for old water discharge through macropores in a steep, humid catchment, *Water Resour. Res.*, *26*(11), 2821–2832.

McGlynn, B. L., J. J. McDonnell, J. Seibert, and C. Kendall (2004), Scale effects on headwater catchment runoff timing, flow sources, and groundwater-streamflow relations, *Water Resour. Res.*, *40*, W07504, doi:10.1029/2003WR002494.

Mohn, J., A. Schürmann, and F. Hagedorn (2000), Increased rates of denitrification in nitrogen-treated forest soils, *For. Ecol. Manage.*, *137*, 113–119.

Moore, R. D., and J. C. Thompson (1996), Are water table variations in a shallow forest soil consistent with the TOPMODEL concept?, *Water Resour. Res.*, *32*(3), 663–669, doi:10.1029/95WR03487.

O'Loughlin, E. M. (1986), Prediction of surface saturation zones in natural catchments by topographic analysis, *Water Resour. Res.*, *22*(5), 794–804. Penna, D., N. Mantese, L. Hopp, M. Borga, and G. Dalla Fontana (2014), Spatio-temporal variability of piezometric response on two steep alpine hillslopes, *Hydrol. Processes*, doi:10.1002/hyp, in press.

R Development Core Team (2005), *R: A Language and Environment for Statistical Computing*, R Found. for Stat. Comput., Vienna, Australia.

Rodhe, A., and J. Seibert (2011), Groundwater dynamics in a till hillslope: Flow directions, gradients and delay, *Hydrol. Processes*, *25*(12), 1899–1909, doi:10.1002/hyp.7946.

Schleppi, P., N. Muller, H. Feyen, A. Papritz, J. B. Bucher, and H. Flühler (1998), Nitrogen budgets of two small experimental forested catchments at Alptal, Switzerland, *For. Ecol. Manage.*, *101*, 177–185.

Seibert, J., and B. L. McGlynn (2007), A new triangular multiple flow direction algorithm for computing upslope areas from gridded digital elevation models, *Water Resour. Res.*, *43*, W04501, doi:10.1029/2006WR005128.

Seibert, J., K. Bishop, and L. Nyberg (1997), A test of TOPMODEL's ability to predict spatially distributed groundwater levels, *Hydrol. Processes*, *11*, 1131–1144.

Seibert, J., K. Bishop, A. Rodhe, and J. J. McDonnell (2003), Groundwater dynamics along a hillslope: A test of the steady state hypothesis, *Water Resour. Res.*, *39*(1), 1014, doi:10.1029/2002WR001404.

Spearman, C. (1904), The proof and measurement of association between two things, *J. Psychol.*, *15*, 72–101, doi:10.1093/ije/dyq191.

Spence, C., and M. Woo (2006), Hydrology of subarctic Canadian Shield: Heterogeneous headwater basins, *J. Hydrol.*, *317*(1–2), 138–154, doi:10.1016/j.jhydrol.2005.05.014.

Spence, C., X. J. Guan, R. Phillips, N. Hedstrom, R. Granger, and B. Reid (2009), Storage dynamics and streamflow in a catchment with a variable contributing area, *Hydrol. Processes*, *24*(16), 2209–2221, doi:10.1002/hyp.7492.

Tarboton D. G. (1997), A new method for the determination of flow directions and upslope areas in grid digital elevation models, *Water Resour. Res., 33–2*, pp. 309–319.

Travis, M. R., W. D. Iverson, H. Gary, and C. G. Johnson (1975), VIEWIT: Computation of seenarea, slope and aspect for land-use planning PSW 11, *Gen. Tech. Rep. PSW-GTR-11*, U.S. Dep. Agric. – For. Serv., Berkeley, Calif.

Troch, P. A., M. Mancini, C. Paniconi, and E. F. Wood (1993), Evaluation of a distributed catchment scale water balance model, *Water Resour. Res.*, *29*(6), 1805–1817.

Tromp-van Meerveld, H. J., and J. J. McDonnell (2006), Threshold relations in subsurface stormflow: 2. The fill and spill hypothesis, *Water Resour. Res.*, *42*, W02411, doi:10.1029/2004WR003800.

Tromp-van Meerveld, H. J., N. E. Peters, and J. J. Mcdonnell (2007), Effect of bedrock permeability on subsurface stormflow and the water balance of a trenched hillslope at the Panola Mountain Research Watershed, Georgia, USA, *Hydrol. Processes*, *21*, 750–769, doi:10.1002/hyp.

Uchida, T., Y. Asano, N. Ohte, and T. Mizuyama (2003), Seepage area and rate of bedrock groundwater discharge at a granitic unchanneled hillslope, *Water Resour. Res.*, *39*(1), 1018, doi:10.1029/2002WR001298.

U.S. Department of the Interior (2001), *Water Measurement Manual*, 3rd ed., U.S. Gov. Print. Off., Washington, D. C.

Zehe, E., R. Becker, A. Bardossy, and E. Plate (2005), Uncertainty of simulated catchment runoff response in the presence of threshold processes: Role of initial soil moisture and precipitation, *J. Hydrol.*, *315*(1–4), 183–202, doi:10.1016/j.jhydrol.2005.03.038.